

Hall-effect in $\text{LuNi}_2\text{B}_2\text{C}$ in normal and superconducting mixed states

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Abstract

The Hall resistivity ρ_{xy} of $\text{LuNi}_2\text{B}_2\text{C}$ is negative in the normal as well as in the mixed state and has no sign reversal typical for high- T_c superconductors. A distinct nonlinearity in the ρ_{xy} dependence on field H was found in the normal state for $T \lesssim 40$ K, accompanied by a large magnetoresistance reaching +90% for $\mu_0 H = 16$ T at $T = 20$ K. The scaling relation $\rho_{xy} \sim \rho_{xx}^\beta$ (ρ_{xx} is the longitudinal resistivity) was found in the mixed state, the value of β being dependent on the degree of disorder.

Keywords: A. superconductors, D. electronic transport, D. galvanomagnetic effects.

Investigations of the Hall effect in the normal and superconducting (SC) mixed states give an important information about the electronic structure and the vortex dynamics. The nature of both of them is not settled yet for the recently discovered [1,2] SC borocarbides $R\text{Ni}_2\text{B}_2\text{C}$ ($R=\text{Y}$, rare earth). Despite the fact that the borocarbides have a tetragonal layered crystal structure, their electronic properties indicate three-dimensionality showing little anisotropy [3–5]. Interesting features of some borocarbides ($R=\text{Lu}$, Er) are their unusual square vortex lattice [6] and, connected with that, the anisotropy of the critical magnetic field $H_{c2}(T)$ in the ab -plane [7,8]. Since the Hall effect in the SC state may depend on peculiarities of the vortex lattice, its study is of special interest for systems with an anomalous square vortex lattice. To our knowledge, no data on the Hall effect for $\text{LuNi}_2\text{B}_2\text{C}$ and only few for other borocarbides are known so far [9–12]. For the compounds based on $R = \text{Y}$ [9–11], Ho [9,11], La [9], and Gd [11], it was observed that the normal state Hall coefficients R_H are negative and only slightly temperature dependent. At the same time, a negative but strongly temperature-dependent R_H was found for the heavy-fermion-like compound $\text{YbNi}_2\text{B}_2\text{C}$ [12]. No sign reversal of the Hall resistivity ρ_{xy} typical for high- T_c superconductors was observed for $\text{YNi}_2\text{B}_2\text{C}$ [10], but the mixed state Hall effect was not studied for borocarbides systematically.

The mixed state Hall effect was investigated mainly for high- T_c SC. Two unexpected effects were found: sign reversal of ρ_{xy} for $T < T_c$ and a striking scaling relationship between ρ_{xy} and the longitudinal resistivity ρ_{xx} in the SC transition region, $\rho_{xy} \sim \rho_{xx}^\beta$. *Sign reversal* of ρ_{xy} has been observed for several types of high- T_c SC, e.g., $\text{YBa}_2\text{Cu}_3\text{O}_{7-y}$ [13,14], $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ [14,15], $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ [16] as well as for some low- T_c SC: In-Pb alloys, V, Nb (see [17]). Several models have been proposed for the description of this effect [18–20], but its nature is not yet fully understood. Meanwhile, in [19,20], the sign reversal of ρ_{xy} below T_c is expected to be not a universal property, but crucially dependent on the shape of the Fermi surface. *Scaling behavior*, $\rho_{xy} \sim \rho_{xx}^\beta$, in the SC state was observed e.g. for $\text{YBa}_2\text{Cu}_3\text{O}_{7-y}$ ($\beta=1.7$) [21], $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ ($\beta \approx 2$) [15], and $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ ($\beta \approx 2$) [16]. This has been interpreted [22] in the framework of glassy scaling near a vortex-glass transi-

tion. Considering the effect of flux pinning on the Hall conductivity, σ_{xy} , it is expected that σ_{xy} is independent of the degree of disorder [23]. Scaling behavior, $\rho_{xy} = A\rho_{xx}^\beta$ with $\beta = 2$, is believed to be a general feature of any vortex state with disorder-dominated dynamics [23]. On the other hand Wang, Dong and Ting (WDT) [24] developed a theory for the Hall effect including both pinning and thermal fluctuations. Scaling and sign reversal of ρ_{xy} are explained by taking into account the backflow current due to pinning [24]. Thereby, β changes from 2 to 1.5 as the pinning strength increases [24]. Controversial experimental results have been reported on the influence of disorder on the mixed state Hall effect. Thus, for $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ irradiated by heavy ions, $\beta = 1.85$ holds even after irradiation [16]. On the other hand, for irradiated $\text{YBa}_2\text{Cu}_3\text{O}_{7-y}$ samples, β was found to be 1.5 ± 0.1 compared to 2 ± 0.2 for unirradiated ones [25] in accordance with WDT.

In this communication, we report the Hall effect study for $\text{LuNi}_2\text{B}_2\text{C}$. In the normal state, a negative and weakly temperature dependent R_H was observed. Contrary to the case of $\text{YNi}_2\text{B}_2\text{C}$, the $\rho_{xy}(H)$ dependence was found to be essentially nonlinear for $T \lesssim 40$ K, accompanied by a very large magnetoresistance MR. In the SC transition region, scaling behavior was found, but no sign reversal of ρ_{xy} was observed. The scaling exponent β was found to be dependent on the degree of disorder and can be varied by annealing. This is attributed to a variation of the strength of flux pinning.

Polycrystalline $\text{LuNi}_2\text{B}_2\text{C}$ (in the following denoted as PC AN) was prepared by arc-melting in Ar atmosphere and subsequent annealing at 1100 °C, as described in more detail in [26]. The phase purity of the samples was checked by X-ray diffraction. The reflexes reveal practically a single phase. For comparison, some measurements were performed on an unannealed sample (PC UNAN). Hall contacts with typical misalignment of less than 0.1 mm were used (typical dimensions of the samples were $3 \times 1 \times 0.3$ mm³). The Hall voltage was measured for two directions of the field H . MR was measured by standard four-probe method. Most measurements were done at $\mu_0 H$ up to 5 T, but some of them up to 16 T in different installation.

The ρ_{xx} vs. T curves for PC AN are shown on the inset of Fig. 1. The value of $\rho_{xx}(17\text{ K})$

is $2.7 \mu\Omega\text{cm}$, which is comparable with that of $\text{LuNi}_2\text{B}_2\text{C}$ single crystals ($1.9 \mu\Omega\text{cm}$ [8] and $2.5 \mu\Omega\text{cm}$ [27]). The residual resistance ratio $\text{RRR}=\rho_{xx}(300 \text{ K})/\rho_{xx}(17 \text{ K})$ is 41 for PC AN which is significantly higher than for single crystals (25 [8] and 27 [27]). The value of $T_c=16.7 \text{ K}$ is also slightly higher than that reported for single crystals (15.8 K [7], 16.1 K [8], 16.5 K [27]). The width of the SC transition is 0.27 K which is close to the values $0.2\div 0.25 \text{ K}$ typical for single crystals [7,8,27]. These results give evidence for a good quality of the PC AN sample. PC UNAN has the lower value of T_c (14.7 K) and an order of magnitude higher value of $\rho_{xx}(17 \text{ K})$ (not shown in a figure).

The results for $H_{c2}(T)$ are depicted on Fig. 1. (H_{c2} was determined as in [7] by the extrapolation of the *ac*-susceptibility curve to zero susceptibility value.) For comparison, the data from [7] for a single crystal (SCR) with $H \parallel \langle 110 \rangle$ are also shown (as open circles). The upper curvature (UC) in $H_{c2}(T)$, near T_c , is clearly visible. Note that, in accordance with [27], the UC region is smaller for the unannealed sample.

The Hall resistivity $\rho_{xy}(H)$ of both samples in normal and SC states is shown in Fig. 2. At $3.3 \text{ K} \leq T \leq 300 \text{ K}$, ρ_{xy} is negative and has no sign reversal.

In the normal state, a pronounced nonlinearity in the $\rho_{xy}(H)$ dependences is evident for $T \lesssim 40 \text{ K}$, which is more clearly seen in the insets of Fig. 2 where some results obtained for H up to 16 T are presented. It should be underlined that no nonlinearity in $\rho_{xy}(H)$ was reported for $\text{YNi}_2\text{B}_2\text{C}$ [10] and $\text{YbNi}_2\text{B}_2\text{C}$ [12].

In Fig. 3, the $R_H(T)$ dependence of the PC AN sample is shown for $\mu_0 H=5 \text{ T}$. At $T \lesssim 40 \text{ K}$, $R_H(T)$ deviates from the linear behavior observed for high T (dotted line). This deviation is connected with the nonlinearity in $\rho_{xy}(H)$ at low T , shown in Fig. 2. The value of R_H is comparable with those reported for $\text{YNi}_2\text{B}_2\text{C}$ [9–11], but it is five times smaller than the value $R_H(T)=3\cdot 10^{-7} \Omega\text{cm}/\text{T}$ obtained from band structure calculations [4]. These deviations may be caused by correlation effects in borocarbides. The evaluation of the carrier density from the R_H value at $T=300 \text{ K}$, by using a single band model which is a rough approximation, gives 1.5 carriers per unit cell.

As can be seen from Fig. 4, the values of $\text{MR}=(\rho_{xx}(H) - \rho_{xx}(0))/\rho_{xx}(0)$ for the PC AN

sample at $T = 20$ K are as high as 25 and 90% for $\mu_0 H = 5$ and 16 T, respectively [30]. Note that an MR of only $\approx 7.3\%$ was observed, at $\mu_0 H = 4.5$ T and $T = 20$ K, for a $\text{LuNi}_2\text{B}_2\text{C}$ single crystal with $\text{RRR} = 25$ (H parallel to the tetragonal c -axis) [8]. A possible reason for the significantly larger MR for the polycrystalline sample compared to the single crystal [8] is the formation of open orbits on the Fermi surface of $\text{LuNi}_2\text{B}_2\text{C}$ for $H \perp c$. (The possibility of the open orbits formation for borocarbides was pointed out in band structure calculations [5,3]. It was claimed that one part of the Fermi surface is a cylinder along the c -axis [5], so open orbits can be expected for $H \perp c$.) It is well known [31] that open orbits can lead to large values of $\text{MR} \sim H^2$, whereas closed orbits should give rise to saturation of $\text{MR}(H)$ for large H . In that case the averaging of MR should lead to a practically linear $\rho(H)$ dependence for polycrystals [31] that should be *stronger* than that observed for single crystals for $H \parallel c$ when only closed orbits could be expected. Therefore, significantly larger MR observed for the polycrystals compared to one for the single crystal for $H \parallel c$ can be considered as an indication for the open orbits formation in $\text{LuNi}_2\text{B}_2\text{C}$ for $H \perp c$. Measurements of the MR in high fields for single crystals with two configurations ((i) $I \parallel c$ and $H \perp c$ and (ii) $I \perp c$ and $H \parallel c$) are necessary to check this hypothesis.

The nonlinear $\rho_{xy}(H)$ dependence and the large MR, found by us, as well as the anisotropy of H_{c2} in the ab -plane and the square vortex lattice, reported for $\text{LuNi}_2\text{B}_2\text{C}$ at high H earlier [6], may be caused by the peculiarities of its electronic structure, because for $\text{YNi}_2\text{B}_2\text{C}$ all these anomalies are absent. (For $\text{YNi}_2\text{B}_2\text{C}$ a linear $\rho_{xy}(H)$ dependence, a substantially smaller MR [10,30], and only a very small anisotropy of $H_{c2}(T)$ [8] were observed.) These distinctions are probably connected with the difference between the Fermi surfaces of the two compounds. For the borocarbides, the Fermi surface topology is very sensitive to the position of the Fermi level [3], that may be slightly different for the two cases, Lu and Y, due to, e.g., different lattice constants. From our results [30] it follows, that the formation of open orbits is probably easier in case of $\text{LuNi}_2\text{B}_2\text{C}$.

As shown in the inset of Fig. 4, the nonlinearity in $\sigma_{xy}(H)$ is even more pronounced than for $\rho_{xy}(H)$ ($\sigma_{xy} \cong \rho_{xy}/\rho_{xx}^2$, $\rho_{xx} \gg |\rho_{xy}|$). In particular, σ_{xy} is practically independent

of H for $\mu_0 H = 8 \div 16$ T, at $T = 4.5 \div 20$ K. The nonlinear $\rho_{xy}(H)$ dependence and the large MR of $\text{LuNi}_2\text{B}_2\text{C}$ are probably closely connected and result in a practically constant $\sigma_{xy}(H)$ for high fields. The reason why σ_{xy} is independent of H for high fields, resulting in $\rho_{xy} \sim \rho_{xx}^2$ in the *normal state* is not yet understood. (Noteworthy, $\rho_{xy} \sim \rho_{xx}^2$ scaling in the *normal state* was observed also for the SC heavy fermion compound UPe_{13} [28].) A nonlinear $\rho_{xy}(H)$ dependence can also be obtained within the two-band model used, e.g., to interpret the nonlinear and even nonmonotonous $\rho_{xy}(H)$ dependence for UB_{13} [28]. In this model, at low H , the light carriers with high mobilities give the prevalent contribution to $\rho_{xy}(H)$, whereas in high fields the contribution of the heavier carriers are more significant. Recently, in a different multi-band model [27], proposed for the Lu- and Y-borocarbides, the existence of at least two bands with significantly different Fermi-velocities was found to be essential for the quantitative description of $H_{c2}(T)$ curves. Note that several groups of carriers with different masses have been directly observed for $\text{YNi}_2\text{B}_2\text{C}$ in dHvA experiments [29].

In the *mixed state*, two regions concerning the behavior of ρ_{xy} and ρ_{xx} can be distinguished (see Fig. 5). For higher values of H (or $|\rho_{xy}|$ or ρ_{xx}) it is clearly seen that the scaling behavior $|\rho_{xy}| = A\rho_{xx}^\beta$ holds for both samples. The value of β is 2 ± 0.1 for PC AN and it decreases to 1.7 ± 0.1 for PC UNAN that has an order of magnitude higher resistivity. This may be connected, in accordance with WDT, with an increase of pinning effects. For decreasing fields, ρ_{xx} vanishes at lower values of H than $|\rho_{xy}|$ (see the insets of Fig. 5), which is also consistent with theoretical predictions in [24]. Obviously, pinning effects are essential for the Hall effect in $\text{LuNi}_2\text{B}_2\text{C}$.

In order to understand the absence of sign reversal in ρ_{xy} for $\text{LuNi}_2\text{B}_2\text{C}$, the following physical picture of the Hall effect in the mixed state [19,20] can be used in addition to WDT theory: there are two contributions to σ_{xy} in the SC state, $\sigma_{xy} = \sigma_n + \sigma_{sc}$, where σ_n is connected with normal carriers that experience a Lorentz force in the vortex core and σ_{sc} is an anomalous contribution connected with the motion of vortices parallel to the electrical current I . In [19] and [20] it was claimed that $\sigma_{sc} \sim 1/H$ and could have a sign opposite

to that of σ_n . Therefore, in small H , the $\sigma_{sc}(H)$ term is more essential but in higher fields $\sigma_n(H)$ becomes to be dominant. If σ_{sc} has a different sign than σ_n it is possible to observe sign reversal in $\rho_{xy}(H)$ at $T < T_c$ [19,20]. The relation $\sigma_{xy} = \sigma_n + \sigma_{sc}$ was verified and the term $\sigma_{sc} \sim 1/H$ was observed in [32] for YBCO. For $\text{LuNi}_2\text{B}_2\text{C}$ the conductivity decreases with increasing H as can be seen, for $T=10$ and 4.5 K, from the inset of Fig. 4. It should be pointed out, that the observed σ_{xy} vs. H curves seem to change more rapidly, than $1/H$. A similar behaviour was observed for cuprates, see, e.g., Ref. [33]. Therefore the mechanism of the mixed-state Hall effect connected with vortex motion is assumed to work for borocarbides as well. The signs of σ_n and σ_{sc} are the same, contrary to the case of high- T_c superconductors. This may be the reason for the absence of sign reversal of σ_{xy} in borocarbides.

In conclusion, we have investigated the Hall effect for $\text{LuNi}_2\text{B}_2\text{C}$ in normal and mixed states. A negative and only slightly temperature-dependent R_H was found for $T > T_c$. The value of R_H is five times smaller than that resulting from band structure calculations [4]. Pronounced nonlinearity in the $\rho_{xy}(H)$ dependence was found in the normal state for $T \lesssim 40$ K accompanied by a very large MR. The possibility of open orbits formation on the Fermi surface for $H \perp c$ is pointed out. In the mixed state scaling behavior, $\rho_{xy} \sim \rho_{xx}^\beta$, was observed but no sign reversal typical for high- T_c superconductors was found. The scaling exponent β is 2 ± 0.1 for the annealed sample with low ρ_{xx} and it decreases to 1.7 ± 0.1 for the unannealed one. This is attributed to a variation of the strength of flux pinning.

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FIGURES

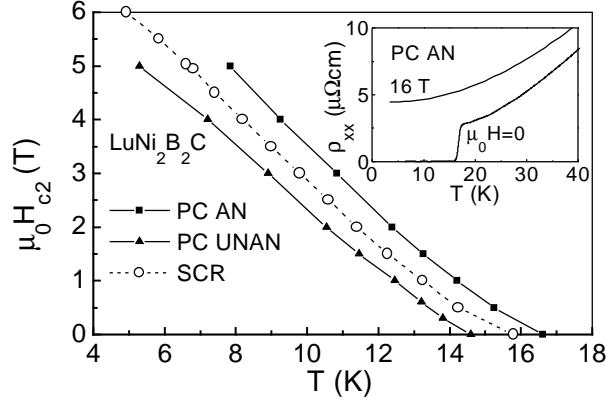


FIG. 1. H_{c2} vs. T for three $\text{LuNi}_2\text{B}_2\text{C}$ samples. Open symbols - the results in Ref. [7] for single crystal. Lines are guides for eye. The inset shows ρ_{xx} vs. T for the annealed polycrystalline sample.

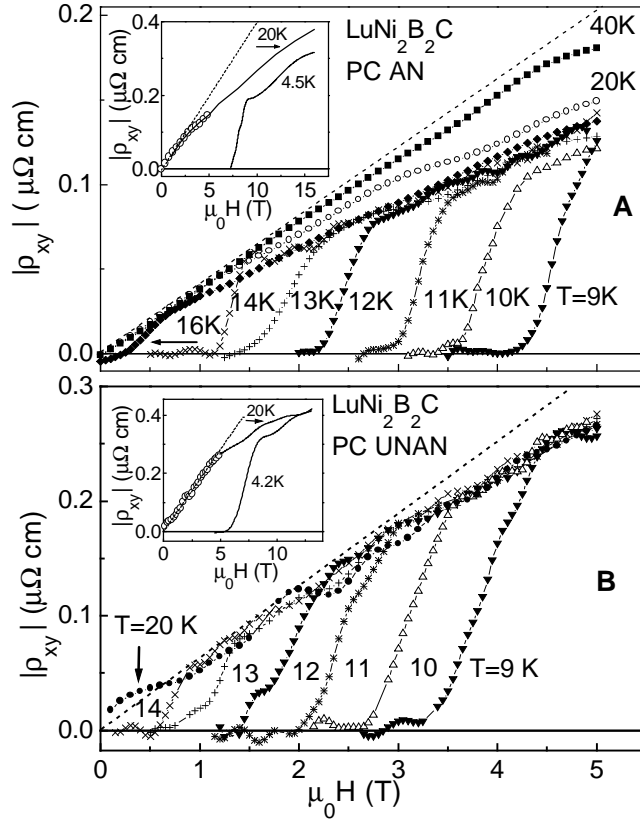


FIG. 2. $|\rho_{xy}|$ vs. H for the annealed (A) and unannealed (B) samples. The dashed lines are low-field asymptotes to the normal state curves. Open points in the insets denote the results obtained for $\mu_0 H \leq 5$ T.

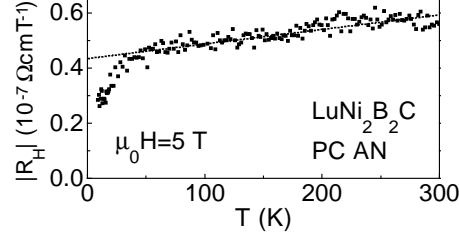


FIG. 3. Absolute value of R_H vs. T for $\text{LuNi}_2\text{B}_2\text{C}$.

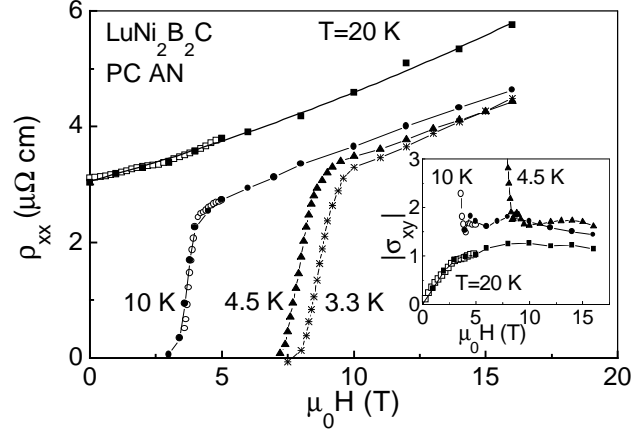


FIG. 4. Magnetoresistance for annealed $\text{LuNi}_2\text{B}_2\text{C}$. In the inset σ_{xy} (in $10^{-2}\mu\Omega^{-1}\text{cm}^{-1}$) vs. magnetic field is shown. Open points denote the results obtained for $\mu_0 H \leq 5$ T. Lines are guides for eye.

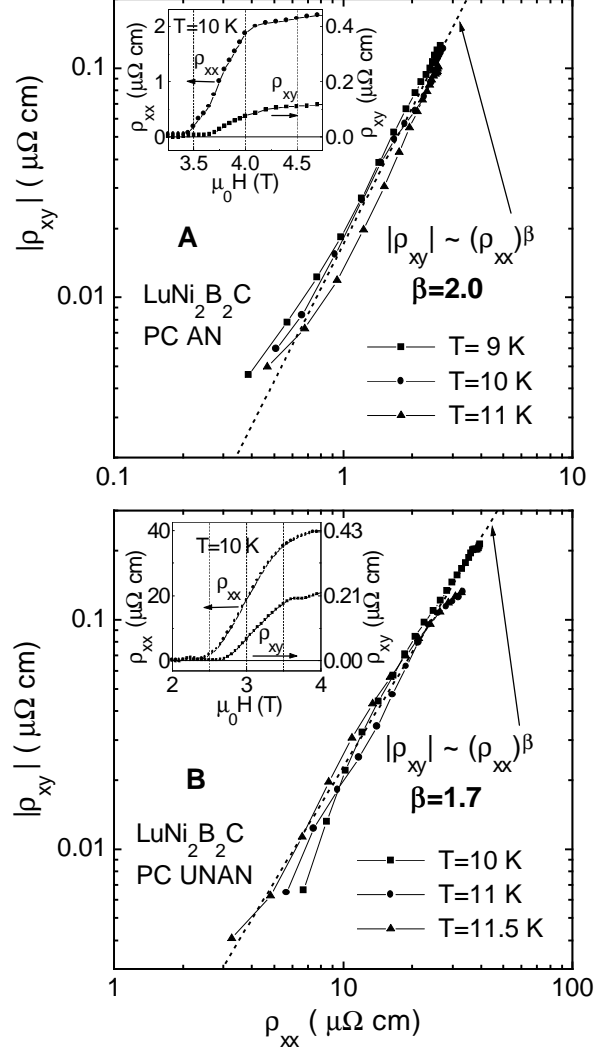


FIG. 5. $|\rho_{xy}|$ vs. ρ_{xx} for the annealed (A) and unannealed (B) samples. In the insets $|\rho_{xy}|$ and ρ_{xx} vs. magnetic field are simultaneously shown.